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DESIGN AND TESTING OF HIGH PERFORMANCE BRUSHES.(U)
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FINAL REPORT

Contract N00014-76-C-1009
July 1, 1976 to Jan.31, 1982

DESIGN AND TESTING OF HIGH PERFORMANCE BRUSHES

Submitted to:

Office of Naval Research
800 N. Quincy Street
Arlington, Virginia 22217
Metallurgy Branch

Submitted by:
Doris Kuhlmann-Wilsdorf
University Professor of Applied Science
University of Virginia
Charlottesville Virginia 22901

SCHOOL OF ENGINEERING AND APPLIED SCIENCE

Report # UVA/525-324/MS82/104
March 1982

UNIVERSITY OF VIRGINIA
CHARLOTTESVILLE, VIRGINIA 22901

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DESIGN AND TESTING OF HIGH PERFORMANCE BRUSHES

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ABSTRACT

A new breed of electrical brush, i.e. unlubricated flexible metal brushes, has been developed. Of these, two specific types, namely metal fiber brushes and metal foil brushes, have been constructed and tested, and a theory has been developed which accounts for their behavior, based on Holm's theory of electrical contacts. It has been shown that electrical tunneling makes a significant contribution to current conduction in fiber brushes, outside of the areas needed for bearing the brush force. Correspondingly brush resistance is reduced, the more so the finer the fibers are, and brush performance was found to be very superior. Some of these developments plus a number of other novel designs of unlubricated flexible metal brushes have given rise to two extensive patent applications. The most promising of those latter designs have not yet been reduced to practice but they should go far to eliminate most, and perhaps all, of remaining shortcomings of electrical brushes. In this, the outstanding properties are (i) very low brush resistance even at quite small brush forces, (ii) virtual absence of electrical noise. As an integral part of our research, testing equipment has been developed which permits testing of electrical brushes at constant loads as small as 0.1 N at currents up to 500 Amp and speeds to 72m/s, while monitoring the brush resistance, noise, wear and coefficient of friction. The experience gained with electrical brushes opened the way to the development of a new theory of unlubricated metal friction and wear, as also theoretical understanding of metal-graphite brushes, for which two distinct regimes of conduction were discovered. In addition, some theoretical research in other areas of ancillary interest to brush behavior has been conducted, most of it in metal fatigue. Altogether twentysix papers were published in the international literature, one book edited, two patent applications (with 102 and 107 claims, respectively) made, and three advanced degrees completed (two M.S. and one Ph.D. degree).

INITIAL GOALS AND BACKGROUND INFORMATION

The initial proposal was made in response to a call for assistance in overcoming a bottleneck which had arisen in connection with the development of compact homopolar motors and generators, in that no known electrical brushes were capable of meeting the design requirements, namely a current density of 2000 A/in^2 = 3.1 MA/m^2, at a speed of 40 m/s at a total loss of 0.25 watt/amp or less. At the time of the request, the best candidate brushes were the SG-142 (Stackpole, 75w/o Ag in graphite) run in a moistened argon atmosphere, and a fiber brush made of 8 μm silver-plated graphite fibers (McNab, U.S.Patent 3,668,451). This choice represented the implicit, perhaps unconscious restriction of brush specialists that all electrical brushes had to be lubricated, and that among the two available lubricants, namely graphite and molybdenumdisulfide, only the former had a sufficiently low electrical resistivity to serve the purpose. The choice of atmosphere arose presumably from a combination of practical eperience and theoretical knowledge. It has the desired features

of inhibiting the formation of unwanted surface films, such as of oxides, sulfides, chlorides or carbonates, and at the same time provides moisture to the graphite without which graphite does not lubricate but rapidly disintegrates through dusting.

GUIDING IDEAS

The total power loss through an electrical brush is the sum of mechanical loss and electrical loss. These depend on the applied brush force in opposite directions, i.e. the electrical resistance, and hence the electrical loss, decreases with increasing brush force, but the mechanical loss is proportional to the brush force. As a general rule, the loss is therefore minimized when the two losses are equal to each other, and this means that the optimal brush force drops with increasing velocity since the mechanical loss is proportional, also, to the velocity. However, one cannot arbitrarily reduce the brush force because the brush must at all times be kept in firm contact with the opposite side. If not, arcing results which is very destructive to brushes. The magnitude of the minimum force needed to keep the brush running smoothly decreases with increasing mechanical compliance of the brush, but the typical solid metal-graphite brushes are rigid and therefore require a rather high brush force, for that reason making them unsuitable for high speed applications if at the same time the total loss shall be kept at a minimum.

The electrical resistance of a brush, which determines the electrical power loss, consists of three parts: The ohmic resistance of the brush body, the constriction resistance (due to the fact that atomic contact between two solids is restricted to a small number of contact spots, the "a-spots", through which all of the current must pass, thusly forcing local constriction of the flow line pattern), and the film resistance. The latter is due to surface films separating the two sides at the a-spots.

In view of these facts, it was decided to construct metal fiber brushes (or metal "velvet" brushes) in the anticipation that these would reduce, and partly eliminate, all three restrictions that prevent brushes to attain the desired high performance levels: Breaking the tradition of using graphite lubrication would mean that the film resistance of the lubrication layer would be eliminated. Providing very many a-spots, namely at the ends of all metal fibers making contact with the opposite side, would practically eliminate the constriction resistance since this is inversely proportional to the root of the number of a-spots. And making the brush mechanically soft would permit the use of very light brush forces, and thus permit to greatly reduce the mechanical loss.

TRANSFORMING THE GUIDING IDEAS INTO PRACTICE - PROJECTS UNDERTAKEN

From the outset, the research appeared to divide quite naturally into three major tasks:

1) Designing and constructing testing equipment which would permit to pass currents up to about 500 Amp through brushes while they were loaded against a rotor with predetermined constant forces as low as about 0.5 oz., i.e. 0.15N, and to monitor the voltage drop and coefficient of friction for minutes, hours or days. Furthermore, the apparatus should permit use of protective atmospheres.

2) Designing and fabricating metal fiber brushes with fiber diameters between, say, 5 and 50 μm, uniformly distributed (brushes of thicker fibers are readily made from fine wires or cables)

3) Testing those brushes and, for comparison purposes, also testing SG-142 brushes. Then, on the basis of experience gained, improving brush design.

Soon it became apparent that three other projects should be pursued concurrently in order to best further the objectives of the research:

4) Develop a theoretical understanding of the electrical resistance of unlubricated metal contacts.

5) Expand the range of unlubricated flexible metal brush designs beyond that of the simple fiber brush by adding the study of metal foil brushes.

6) Continue work on some ancillary research projects relevant to brush behavior either directly or indirectly, including theoretical work on mechanical properties of metals.

After the first few years of this project, the importance of the purely mechanical behavior of the brushes became increasingly obvious. As a consequence a last, but by no means least, research project was added to the list:

7) Develop a theoretical understanding of friction and wear with and without current flow.

ACHIEVEMENTS

The results obtained were as follows, using the same numbers as above:

1) Testing equipment was developed which fulfilled all of the requirements listed under 1) above, and in addition permits monitoring the sum of the elastic deformation and wear rate of the brushes continuously within better than .001". Two papers describing that equipment have been published.

2) Metal fiber brushes with fiber diameters down to about 2 μm and up to ∿100μm at packing fractions between about 20% and 3% were made by successive drawing and bundling in stages until the desired fiber diameters were achieved, then etching away the matrix material surrounding the fibers in the drawn brush stock. The method was published. Fiber materials used were gold, platinum, palladium, niobium, silver and copper.

3) Properties of fiber brushes were found to be indeed quite superior to those of lubricated brushes. Soon the desired limits of performance, i.e. 0.25 w/A at 40m/s and 3.1 MA/m^2, were approached, and in due course they were substantially bettered. As a result it is believed that the bottleneck on account of which this research was carried out has indeed been overcome. It seems that unlubricated metal to metal contact brushes, lightly loaded and with a large number of a-spots, will be used not only in the homopolar machines originally at issue, but probably in a wide range of other high-technology applications. One thus may foresee an increasingly important role of compliant unlubricated metal brushes in the future.

4) A theory of electrical resistance of unlubricated metal brushes has been developed taking Holm's contact theory as a starting point. Unlike metal-graphite brushes, unlubricated metal brushes exhibit no apparent dependence of resistance on current and speed if they are used under clean conditions. This agrees with theoretical expectations for the case that the surface films are so thin (i.e. a few atomic diamters) that they conduct primarily via electron tunneling. The data indicate that electron tunneling outside of the load-bearing a-spots makes a significant contribution to the current conduction when fiber diameters are less than about 50 μm at more than 10% packing fraction. This causes the corresponding decrease of brush resistance as compared to brushes with thicker fibers. Theoretical projections are that tunneling becomes dominant, and brush resistances correspondingly very small, when fiber diameters d and packing fractions f are such that $d/f^{2/3} \lesssim 56\mu m$. Brushes fulfilling this condition have been named QM brushes. If they fulfil their theoretical promise, they will solve all conceivable brush problems in regard to limits on permissible losses per ampere and current densities. Patent applications have been made regarding numerous concepts of methods of making and using such brushes and designs for their shapes.

5) Metal foil brushes have been made and tested. They show great promise for a wide range of applications. They consist of stacks of thin metal foils. Through adjustments of the number, thickness, packing fraction and length of the foils, the

mechanical stiffness of foil brushes can be varied widely, in accordance with intended use. Application of the theory of metallic brushes discussed above rendered excellent agreement between actual and forecast performance, thus greatly strengthening confidence in that theory. The resistance of foil brushes is somewhat higher for same choice of materials load and other conditions, than that of fiber brushes because the a-spots of foil brushes are plastically deformed, whereas those of fiber brushes are mainly elastically loaded. Even so, on account of their great ruggedness and simplicity, together with forecast very high achievable current densities, foil brushes could meet some requirements that cannot be met by monolithic metal-graphite brushes. This research has also been published. It formed the basis for an M.S. degree in Materials Science.

6) Several publications under sponsorship of this program, none of which abstracted from effort which could otherwise have been devoted with comparable effect to brush research, concerned mechanical properties, especially metal fatigue. This subject is of peripheral importance to flexible metal brushes, because the most likely mechanical failure mode of such brushes is through fatiguing of the flexible members. Another ancillary project was to organize a symposium on novel developments and applications of composites, and to edit a book on that symposium. This appeared to be, and almost certainly was, the most effective means to get most up-to-date information on techniques to make fiber brushes. Namely, the brush stock out of which fiber brushes are made is in fact a composite. Whereas our brushes were made through drawing in bundles, another technique is by drawing of metal powders, and yet another through drawing of directionally solidified alloys, or by substituting extrusion wholly or partly for drawing. We obtained numerous samples and practical suggestions for making brushes from participants in the symposium.

7) One of the most fruitful results of the research under this contract has been to clarify the great, hitherto neglected, opportunities which exist in research on friction and wear through teaming mechanical and electrical measurements. Through considering together the results of our measurements on electrical brushes, and the published knowledge on friction and wear of metals (none of which makes any significant use of information from electrical measurements) a new theory of friction and wear could be developed. Quite a few quantitative relationships between the most important parameters, such as speed, normal force, hardness, on the one hand, and coefficient of friction, subsurface deformation, wear rate, etc., on the other hand, have been proposed in that theory. Available evidence generally supports the theory. Two papers have been published on that subject.

Finally one may record some interesting results obtained with SG-142 silver-graphite brushes, being the result of the Ph.D. research of Sara Dillich: It has been shown that two types of surface film can exist on silver-graphite brushes (and by implication on other metal-graphite brushes), one stable only at lower temperature, another at higher. These differ in electrical conductivity and give rise to different coefficients of friction. Through the destruction of the more highly resistive, lubricating film at high current densities, effected through the resultant high surface temperature, those brushes are effectively transformed into unlubricated metal to metal contact brushes, with their correspondingly much lower resistance and higher current-carrying capability. We believe that recorded succcesses with metal-graphite brushes for applications at high speeds and very high pulsed current densities are due to the described transformation, plus perhaps surface melting.

OUTLOOK

At this point it appears that the problem of brushes for high-speed/high current density applications has been resolved, - we trust partly through the research under ONR sponsorship of contract N00014-76-C-1009. In the process of doing that research, very much was learned about the fundamental properties of unlubricated flexible metal brushes, providing a quantitative theory such as does not exist for lubricated brushes. On the basis of this theory, the forecast performance limits of unlubricated flexible metal brushes can be shown to be very much higher than have so far been realized, not only with unlubricated metal brushes but with any type of brush.

Further research in order to follow up on this so far unrealized promise would seem highly desireable, both from a practical standpoint, and for the sake of basic knowledge of contact phenomena and the state of the interface between two conductors in mechanical contact. The practical aspect is of continuing importance because of one property of our brushes which has not yet been mentioned but is highly important, namely that they can be made practically free of electrical noise, and that this can be done at very low brush forces. This is of great relevance in communications, and it is here that perhaps the greatest unmet need of brush improvement persists at this time. Not only that noise limits the reception of faint signals as well as the range of communications at given power, but it is a nuisance and worse in other respects. Thus, we have learned that in Europe electrical tools have to conform to fairly stringent standards in regard to the maximum permissible emission of electrical noise.

As to basic research interests, it has become clear that quantitative understanding of friction and wear can be greatly furthered through combining electrical measurements with mechanical investigations and optical observations. Since we now have reason to rely confidently on the theory of electrical contact resistance, one may use it in combination with measurements of the current- and load-dependence of the electrical resistance to evaluate the nature of the surface film, as well as the approximate size and number of load-bearing contact spots, i.e. those spots at or below which the friction and wear processes in fact take place.

DETAILS OF RESULTS OBTAINED

The research results have been varied and stimulating, as explained above. It appears to be impractical to attempt relating them in greater detail within the framework of this final report. Instead, on the following pages the title pages of the various publications which were produced under sponsorship of this contract are reproduced in chronological order of their completion. The titles and abstracts, together with the references on these will be more complete and self-explanatory than any summary here.

ACKNOWLEDGEMENTS

This research could not have been as effective as we trust it has been, had it not been for the steadfast encouragement and support which we have received from the Office of Naval Research. Our particular thanks are due to the following: Dr. E. I. Salkovitz who made the initial suggestion that we should take an interest in the problems of electrical brushes which until then, i.e. in early 1976, had been totally unknown to any of us. Mr. W. R. Seng who shepherded our project through the first few difficult years and cheered us on when progress seemed to be slow, and who helped us with his excellent technical understanding. Dr. R. A. Burton has been also very supportive as well as most knowledgeable, albeit we did have the pleasure of his cooperation for only about one year. His successor, Commander Harold P. Martin will forever be remembered with much gratitude for his steadfast support in technical as well as administrative matters, and his endeavors to guide the research toward industrial application. Many thanks also go to our colleagues at Westinghouse, among these Dr. I. R. McNab, Dr. P. Reichner, Mr. J. L. Johnson and others, and especially also to those at D.W.T. Naval Research Laboratory, among whom Mr. H. R. Stevens deserves particular mention. - The research at UVA was carried out through the dedicated work of C. M. Adkins, S. Dillich, D. Gerdt, W.L. Gettys, P.B. Haney, V. Srikrishnan and H.G.F. Wilsdorf.

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Dislocation Behavior in Fatigue

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SUMMARY

Recognizing mechanistic similarities as well as differences between unidirectional and cyclic deformation, the authors apply recent advances in understanding mechanisms of unidirectional deformation to fatigue. Reinterpretations or new mechanisms are offered for the following: the formation of dislocation veins and of persistent slip bands (PSB's), the behavior of dislocations in established PSB's, and the transformation of PSB dipolar walls into dislocation cells. In addition, the nature of extrusions and intrusions is discussed.

INTRODUCTION

In the last ten years, interest in the cyclic stress–strain response of materials has intensified, and new methods for designing against fatigue have been developed from the information so far gathered. However, many aspects of cyclic deformation are not properly understood, for example, how persistent slip bands form, and how dislocations subsequently behave in them, and the nature of the walls within persistent slip bands. In this paper, we attempt to develop a detailed story of the mechanisms of cyclic deformation in single phase materials by reviewing and re-interpreting the available evidence and by making use of advances in the understanding of unidirectional deformation.

THE CONNECTION BETWEEN UNIDIRECTIONAL DEFORMATION AND CYCLIC DEFORMATION

The existence of a remarkable similarity in the evolution of dislocation structures for the cases of unidirectional tension and fatigue has been noted repeatedly [1 - 5]. Specifically, the "braids", mainly constituted of primary edge dislocation dipoles, seen in stage I and early stage II of unidirectionally deformed metals, have their counterpart in the loop patches and veining formed in fatigue. Similarly, the more or less well-defined, polygonization-type walls normal to the active slip direction, again composed mainly of primary edge dislocations and primary edge dislocation dipoles, which are seen in stage I and partly in stage II of unidirectionally deformed metals, have their counterparts in the loop walls found in persistent slip bands normal to the primary slip direction in fatigue [6 - 10]. As long as these are fairly narrow and separated from each other, they constitute the so-called ladder structure [6 - 10]. Through merging of persistent slip bands at higher plastic strain amplitudes, the walls may become remarkably extensive and well-defined with rather regular spacing and overall uniform structure [11, 12]. Finally, the cell structure which may form at still higher plastic strain amplitudes out of the wall structure in single crystals [12], or quite generally in polycrystals [1, 13], is the parallel to the cell structure typical for stages II and III in unidirectional strain [5, 14].

Two major differences between the two cases are these:

(i) Due to the typically much larger time spans and total dislocation motion involved, the dislocation structures formed in fatigue are more nearly in their dynamic equilibrium configurations than are those formed in unidirectional strain.

(ii) The oft-repeated to-and-fro motions in fatigue minimize the build-up of local net

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Dislocation behavior in unidirectional deformation and in fatigue

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A fundamental feature common to dislocation configurations formed under a great variety of conditions is that they minimize stored energy among the configurations accessible to the system, or at the least approach such a state more or less perfectly. Different configurations obeying this principle are discussed; and it is shown that their selection depends on the availability of dislocation surplusses of one type and sign only, or of dislocations with only one Burgers vector direction but positive and negative signs, or of dislocations with different Burgers vectors. It is shown that the dislocation configurations observed in unidirectional deformation and in fatigue differ because, in the former, dislocation surplusses of one sign are common, but not in the early and intermediate stages of fatigue. In all of the structures considered, however, long-range dislocation stresses are screened.

In the case of unidirectional strain, dislocation surplusses of one sign and with different Burgers vectors tend to be available locally in stages II and III. Due to stress-screening, the links in the configurations can typically bow-out at stresses not much above the level of the Frank-Read stress which is governed by the line tension of the dislocations and the link length. This, then, controls the momentary flow stress in unidirectional deformation. Work-hardening results from the gradually increasing dislocation density and the concomitant shortening of the average free dislocation link lengths. A simple derivation of stage II work-hardening is given on this basis. Stage III results when similitude breaks down and the dislocation pattern (in the form of dislocation cells) no longer shrinks in scale as the stress increases, even while the dislocation density continues to increase.

The dislocation behavior and movements taking place in fatigue can be qualitatively understood using the same principles applying to unidirectional deformation but with suitable modifications. A quantitative treatment is not yet possible beyond some simple rules regarding the major parameters in the structure underlying persistent slip bands.

1. INTRODUCTION

While the phenomena and characteristics of plastic deformation are varied indeed, the workhardening curve observed in the tensile deformation of most specimens is of very simple type. In the case of single crystals, it is the well-known three-stage workhardening curve which, by the superimposition according to the different orientations plus some extra hardening, is the origin of the workhardening curves of polycrystalline materials, except that in polycrystals the first stage is usually missing. Indeed, Stage I is somewhat erratic, depending sensitively on specimen size, crystal orientation, purity, type of loading, rate of deformation, type of testing machine used, and other parameters. Much about Stage I is understood. It seems that this is the stage in which the dislocation density is still so small that the dislocations interact more strongly with other defects and with the specimen surface than with each other, and thus Stage I has no general significance for our understanding of workhardening. Correspondingly, we shall consider it no further.

As to the remainder of the workhardening curve, it is, as indicated already, rather similar for single and polycrystals and is in fact surprisingly persistent

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EXPERIMENTAL AND THEORETICAL OBSERVATIONS ON THE RELATIONSHIP BETWEEN DISLOCATION CELL SIZE, DISLOCATION DENSITY, RESIDUAL HARDNESS, PEAK PRESSURE AND PULSE DURATION IN SHOCK-LOADED NICKEL

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Abstract—Dislocation density and dislocation cell sizes have been measured along with residual hardness in nickel shockloaded with peak pressures ranging from 80 to 460 kbar at a constant pulse duration of 2 μs, and similarly for 0.5 to 6 μs shock pulse duration at a constant peak pressure of 250 kbar. The dislocation cell size was found to be inversely proportional to the square root of the dislocation density ($d\sqrt{\rho} \cong 15$), consistent with the "principle of similitude", as well as to the peak pressure (i.e. $P = k/d$) in accordance with a widely observed empirical law. The residual dislocation cell size and dislocation density were observed to remain essentially constant in the range of 1–6 μs pulse duration, suggesting that the rate at which dislocations can move into cell configurations lies somewhat below this value. The residual hardness increases with decreasing cell size, but not linearly, and saturates over the range of shock pulse durations investigated at constant peak pressure. When *these measurements are evaluated in* terms of the mesh-length theory of work-hardening, an apparently good agreement is found and the data reveal a high degree of internal consistency within the limits of experimental error. However, the effective resolved shear stress on the active glide systems is found to be a constant but unexpectedly low fraction of the peak pressure, namely about 1 1/2%. Moreover, at the very high shock pressures used, the Peierls-Nabarro stress might have been too high to permit dislocations to move into the observed sub-boundary configurations. Consistent explanations for all of the observations are possible whether or not the Peierls stress under pressure should have been high. In the former case, the dislocation cells formed only at the very end of the shock, when the shock pressures were already well below their peak values. The low value of the computed flow stress arises because the shock generated an essentially hydrostatic pressure. There should have in fact been no slip if it had not been for small deviations from hydrostatic pressure conditions. The rate of work hardening appears to have been 3–4 times higher than for the same strain in tensile testing. Imperfect cell formation and a high rate of dislocation retention is believed to be responsible.

Résumé—On a mesuré la densité de dislocations, la taille des cellules de dislocations et la dureté résiduelle dans le nickel déformé par choc, sous une pression maximale variant entre 80 et 460 kbar pendant une durée de choc constante de 2 μs, et aussi pour une durée de choc de 0,5 à 6 μs sous une pression maximale constante de 250 kbar. On a trouvé que la taille des cellules de dislocations était inversement proportionnelle à la racine carrée de la densité de dislocations ($d\sqrt{\rho} = 15$), ce qui est en accord avec le "principe de similitude", ainsi qu'avec la pression maximale ($P = k/d$) selon une loi empirique souvent observée. La taille des cellules de dislocations résiduelles et la densité de dislocations restaient pratiquement constantes pour une durée du choc comprise entre 1 et 6 μs, de sorte que l'on peut penser que la vitesse à laquelle les dislocations peuvent se déplacer pour former des cellules est légèrement inférieure à cette valeur. La dureté résiduelle augmente, mais non linéairement, lorsque la taille des cellules diminue, et elle se sature pour les durées de choc à pression maximale constante étudiées. Lorsqu'on compare ces mesures à la théorie du durcissement par le réseau de dislocations, on trouve un bon accord apparent, de sorte que toutes les données semblent cohérentes, dans les limites de l'erreur expérimentale. On a trouvé toutefois que, si la cission critique réduite sur les systèmes de glissement actifs était constante, elle atteignait de manière inattendue une fraction très faible de la pression maximale, à savoir environ 1,5%. De plus, aux très fortes pressions de choc étudiées, la contrainte de Peierls et Nabarro aurait pu être trop élevée pour permettre aux dislocations d'aller former les configurations de sous joints, que l'on observait. Il est possible de trouver des explications cohérentes de toutes ces observations, que la contrainte de Peierls sous pression soit forte ou non: Dans le premier cas, les cellules de dislocations ne se sont formées qu'à la fin du choc, quand la pression était déjà nettement inférieure à sa valeur maximale. La faible valeur de la contrainte d'écoulement calculée provient du fait que le choc produisait essentiellement une pression hydrostatique. En fait, il n'y aurait pas eu de glissement, s'il n'y avait eu de petites déviations par rapport aux conditions de pression hydrostatique. Le taux de durcissement est, à déformation égale, 3–4 fois plus

ELECTRICAL AND MECHANICAL LOSSES IN SILVER - GRAPHITE BRUSHES

A Thesis

Presented to

the Faculty of the School of Engineering and Applied Science

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In Partial Fulfillment

of the Requirements for the Degree

Master of Science (Materials Science)

by

Sara A. Dillich

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NEW APPARATUS FOR THE TESTING OF ELECTRICAL BRUSHES IN THE LABORATORY

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ABSTRACT

A laboratory apparatus is described which can be constructed at moderate cost for the testing of electrical brushes. The primary objective in the development of this apparatus has been to obtain flexibility in measuring various important parameters pertaining to the performance of electrical brushes. These include the voltage drop between rotor and brushes, frictional coefficients between the brushes and various rotor surface materials and treatments, mechanical loss, and brush wear, to name the most important ones. The measurements can be performed on a continuous basis during testing. Most importantly, the apparatus permits the testing, also, of fiber brushes which may be run at very low loads, even while high currents are passed through the brushes. The apparatus further permits to run the anodic and cathodic brushes on different tracks, to change the angle of attack of the brushes, to vary the rotor speed as well as the current within wide limits, and to cool the rotor and brushes. An environmental chamber permits to run the tests in controlled atmospheres.

INTRODUCTION

While industrial testing of electrical brushes is done very widely and has been the subject of standardization (in the case of monolithic brushes IEEE Standards 116 - 1975) the development of new brushes in small laboratories requires apparatus which ought to be very flexible, so as to be able to vary the testing conditions quickly and easily. At the same time, in innovative basic research, the number of parameters to be studied can be wider, and the demands on the accuracy of the measurements higher than in routine testing. It seems that laboratory apparatus fulfilling most of the enumerated requirements is not commerically available, nor perhaps even extant. Besides, the cost of such apparatus needs to be kept lower for laboratory applications for small research groups than can be justified for industrial testing.

The apparatus described below is a first attempt at the construction of instrumentation that, although not fulfilling all of the wanted characteristics, at the least is serviceable and quite versatile. The major goal in designing the apparatus was to be able to test selflubricating and unlubricated monolithic as well as fiber brushes, with the further requirement that the brush load be measureable and adjustable within rather wider limits than are ordinarily contemplated. To some extent this is also true for the range of testing velocities as well as for the brush currents. The design aimed at a current capability through the brushes of up to 600 Amp, and testing velocities up to 100 meter/sec, while the brush loads should be variable up to ten pounds per brush and be measureable to an accuracy of about ½ ounce or 0.15 N.

Not all of the design parameters have so far been attained, or have not yet been demonstrated by tests, but currents up to 500 Amps can certainly be used and rotor speeds up to 70 meter/sec. With respect to the load measurements, the skill of the experimenter is involved and some improvements are still possible and planned. At this point load measurements are fairly routinely done to an accuracy of 1 ounce, i.e. 0.3N. Brush wear can be measured independently for each brush with a sensitivity of better than a thousandths of an inch, actually about 1/50 mm, and this on a continuous basis during the test.

OVERALL DESIGN

The overall design of most, if not all, brush testing apparatus is alike, since they basically consist of a motor and axle arrangement by means of which the rotor is driven, and appropriate brush holders with loading and current supply devices so as to keep the brushes in steady contact with

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Deviations from Schmid's Law in Uni-Directional Strain

By

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The various causes for deviations from Schmid's law are examined theoretically. The by far largest contribution to such deviations is found to be due to the Peierls-Nabarro force via the "breathing" of the dislocations core volumes in their motion over Peierls hills and valleys. The changes of flow stress resulting from this cause could be as much as 10% of the normal stress component acting on the slip planes of the dislocations, but more typically amount to a few percent, it is believed. The effects of the normal stress component on the formation energy of dislocation cores, and on "jog dragging" or point defect formation, respectively, are of similar magnitude. Together, they cause a fractional change of the flow stress about equal to the ratio of the observed flow stress to the value of the modulus of rigidity. While these effects are probably noticeable but not important in normal tensile tests and situations which these are designed to simulate, they are believed to have great potential importance in at least three areas: 1) friction and wear, 2) deformations at very high speeds, and 3) deformations under very high pressures, including those encountered in advanced technology, in deep sea applications, and in the earth's interior.

Die verschiedenen Gründe für Abweichungen vom Schmidschen-Gesetz werden theoretisch untersucht. Es wird gefunden, daß der bei weitem größte Beitrag zu derartigen Abweichungen durch die Peierls-Nabarro-Kraft über das „Atmen" der Versetzungskernvolumina bei ihrer Bewegung über Peierls-Hügel und -Täler verursacht wird. Die daraus resultierenden Änderungen der Flußspannung können bis zu 10% der Normalkomponente der Spannung betragen, die auf die Gleitebene der Versetzungen wirkt, jedoch wird angenommen, daß ein Betrag von einigen Prozent typischer ist. Die Einflüsse der Normalkomponente der Spannung auf die Bildungsenergie der Versetzungskerne und auf „jog-dragging" oder bzw. Punktdefektbildung sind von ähnlicher Größe. Zusammen erzeugen sie eine Teiländerung der Flußspannung, die etwa gleich dem Verhältnis der beobachteten Flußspannung zu dem Wert des Festigkeitsmoduls ist. Während diese Effekte wahrscheinlich bemerkenswert jedoch nicht wesentlich sind bei den normalen Bruchtests und Situationen, die angelegt sind, diese zu simulieren, so wird jedoch angenommen, daß sie eine große potentielle Bedeutung in wenigstens drei Fällen haben: 1) Reibung und Verschleiß, 2) Deformationen bei sehr hohen Geschwindigkeiten und 3) Deformationen unter sehr hohen Drücken, einschließlich der in fortgeschrittenen Technologien angetroffenen, in Tiefseeanwendungen und im Erdinneren.

1. Introduction

Ever since the early pioneering research on slip in metals, the validity of Schmid's law has been axiomatic. According to Schmid's law, the resolved shear stress required to deform a crystal in glide is independent of the magnitude and direction of the normal stress acting on the slip plane. Yet, even the experimental curves used to demonstrate Schmid's law in the book by Schmid and Boas (Fig. 92 in [1]) are compatible with small but significant deviations from Schmid's law; and rather consistently, if careful tests are made to compare the flow stress of similar samples in tension and compression, these show a slightly higher flow stress in compression.

The theoretical foundation of Schmid's law is Colonnetti's theorem which states that the elastic strain energy of internal stress systems is independent of the presence of any arbitrary externally applied stress systems. Correspondingly, the glide motion

[1]) Charlottesville, Virginia 22901, USA.

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Dislocation Behavior in Fatigue
II. Friction Stress and Back Stress as Inferred from an Analysis of Hysteresis Loops

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SUMMARY

Fatigue hysteresis loops obtained by three different authors are evaluated to obtain data for the friction stress and back stress acting on the dislocations. Part of the friction stress is equal in magnitude to the back stress and like it rises roughly in proportion to the root of the cumulative plastic strain. The theoretical discussion of this contribution to friction stress will be given in conjunction with the discussion of the back stress in parts III and IV of this series. The smaller part of the friction stress depends more or less linearly on the number of cycles. It is identified primarily with the stress required for dragging the jogs on the screw dislocations which shuttle to and fro in the matrix channels in accordance with the deductions of part I of this series. Additionally, there may be a yet smaller contribution to the friction stress due to dispersed point defects. This, if it exists, comes to saturation after about 12 cycles. The fact that no contribution to the stress can be identified with the back stress due to the glide dislocations which are spun out and taken up again at the channel–loop patch interfaces indicates that their line tension is quite low. This is understandable on account of their arrangement into tilt wall configurations as well as the local screening of their stresses by reorienting loops in their vicinity. Following up on the corresponding hypothesis in part I, it is suggested that the channel widths in the matrix structure adjust such that, on the average, one jog resides on each screw dislocation segment. If so, the channel width should initially decrease inversely with the number of cycles, and then become constant.

1. INTRODUCTION

In a preceding paper [1] (subsequently referred to as I) some features of dislocation behavior in pure metals were discussed for the particular example of copper single crystals subject to constant-strain push–pull fatigue. This work, together with more recent experimental evidence on the conversion of the matrix structure into a persistent slip band (PSB) structure [2], formed the basis of further theoretical studies of the dislocation behavior in fatigue. These are the subject of the present paper and three further contributions to this series (III - V). Whether additional conclusions will ultimately become possible on the basis of recent electron microscope observations of Stage I cracks in PSBs [3] is not yet clear. The latter investigation indicated that in long-life fatigue fracture can take place in PSBs before cells are formed, in contradistinction to the opinions expressed in I. However, this problem reaches beyond the range of interest of the present paper and III - V. For the time being, the focus remains on the stages before crack formation begins and, again, the behavior of copper single crystals in push–pull fatigue at constant strain amplitude. However, it is confidently believed that the conclusions drawn reach well beyond these restrictive experimental conditions and also have broad relevance for fatigue under a host of other conditions because very basic dislocation properties are involved.

The most important conclusion of I, at the least as far as the present paper is concerned, is that the deformation in matrix channels as well as in PSBs is carried mainly by screw dis-

"Strength of Metals and Alloys" (Proc. ICSMA 5 Aachen, Aug.1979, Eds. P. Haasen, V. Gerold and G. Kostorz, Pergamon, N.Y., 1979, pp.1081 to 1087)

CORRELATING BACK STRESSES AND FRICTION STRESSES WITH DISLOCATION BEHAVIOR IN FATIGUED COPPER SINGLE CRYSTALS

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ABSTRACT

An analysis of the hysteresis loops of copper single crystals oriented for single glide, subjected to push-pull constant amplitude fatigue in the "plateau region," shows that the back stress rises more or less as the root of the cumulative plastic strain, saturating at the onset of persistent slip band formation. The friction stress is composed of three parts. The largest of these is equal to the magnitude of the back stress at the end of each cycle. Another, smaller, part saturates well before the back stress. This part can be readily explained in terms of jog-dragging of the screw dislocations which accommodate the fatigue strain in the channels between the loop patches. The third, rather minor part of the friction stress saturates after roughly a dozen cycles and appears to be due to point defect drag, presumably acting on all dislocations. This analysis implies that the friction stress acting on the dipolar edge dislocations in the loop patches is minor, permitting them to aggregate towards their minimum energy configuration, namely a kind of "Taylor lattice" of alternating positive and negative edge dislocations, thus explaining the loop patches which give the appearance of a second phase embedded in the dislocation-free channel material. It is suggested that the dislocation density in the loop patches rises roughly linearly with the cumulative strain for the reason that in each cycle a constant fraction (about one tenth) of the glide dislocations is trapped by random close encounters with the loops at the loop patch surfaces, and that on account of the low friction stress against prismatic glide, equilibration of the dislocation density takes place continuously throughout the patches. Theoretical arguments strongly suggest that the loops in the loop patches "flip" with each half cycle. This behavior explains, quantitatively, the observed dependence of the back stress on the cumulative strain as well as the equality between the larger part of the friction stress and the back stress. The evolution of the shape of the hysteresis loops with number of cycles that may be derived from this theory is in excellent agreement with observation.

INTRODUCTION

A great deal of excellent experimental work by a number of authors has clarified the defect structure in fatigued single crystals of metals; however, the theoretical understanding has been lagging. It is in this area that the present paper aims to make a contribution, specifically in regard to the dislocation motions occurring in the earlier phases of fatiguing up to the onset of persistent slip band formation. Further, in order to deal with the simplest possible conditions, the particular case of copper single crystals oriented for single glide in push-pull fatigue was chosen.

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Dislocation Behavior in Fatigue
III. Properties of Loop Patches — Do They Participate in Fatigue Cycling ?

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SUMMARY

The fundamental question of whether the loops in the loop patches "flip" rhythmically with fatigue cycling (model 1) or remain randomly oriented throughout (model 2) is considered. It is shown that model 2, but not model 1, gives rise to apparently insurmountable difficulties. These include the fact that the back stress τ_B derived on the basis of model 2 apparently has very different characteristics from those observed. In contrast, model 1 yields qualitative agreement between the predicted and observed properties of the back stress. Further, the remarkable equality $\tau_B = \tau_F - \tau_S$, where τ_F is the friction stress and τ_S that part of the friction stress which has previously been identified with point-defect hardening and jog dragging, is a direct consequence of model 1 but appears to be in irreconcilable conflict with model 2. For these reasons it is concluded that the loops do participate in fatigue cycling, i.e. *model 1 applies.*

Loop patches will behave like Taylor dislocation lattices provided that the frictional stress against prismatic glide of the loops is small. This is believed to be established by the result given in Part II of this series that the contribution to τ_S due to jog dragging is much larger than that ascribable to point-defect hardening and that τ_S is typically much smaller than the applied stress. As a consequence loop patches have a total volume that is determined by the amount of dipoles in the specimen. These are formed by random trapping of glide dislocations. Since the channel width appears to be nearly constant, probably regulated by jog formation as shown in Part II, the average loop patch diameter is thus determined. Also, in contrast to the assumption in Part I of this series, it is now concluded that the properties of the loop patches, except for the surfaces immediately interacting with the glide dislocations, are essentially homogeneous throughout. Except for this correction, the concepts and model developed in this and subsequent parts of the series are largely based on Part I.

A quantitative treatment of the back stress as a function of the number of cycles and the fatigue strain amplitude, and of the evolution of the hysteresis loops, will be given in Part IV. The conversion of the matrix structure into persistent slip bands (PSBs) will be the subject of Part V. This series of papers pertains to fatigue strain amplitudes in the "plateau region" in which PSB formation ensues at about 30 MPa stress.

1. INTRODUCTION

In Part II of this series [1] an analysis of hysteresis loops obtained in the push–pull constant plastic strain amplitude fatigue of copper investigated in three different laboratories [2 - 4] was presented. It was shown that the larger part of the friction stress τ_F derived from the hysteresis loops was equal to the back stress τ_B and varied approximately as $(\gamma_{pl})_{cum}^{1/2}$. Here

$$(\gamma_{pl})_{cum} = 2N\Gamma \tag{1}$$

where $(\gamma_{pl})'_{cum}$ is the cumulative plastic strain, N the number of cycles and Γ the plastic strain range. The friction and back stresses, even though obtained for widely different plastic shear strain ranges Γ, namely 1% [2], 0.5% [3] and 0.3% [4], could essentially be described by one master equation in terms of cumulative strain. The relation

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Dislocation Behavior in Fatigue

IV. Quantitative Interpretation of Friction Stress and Back Stress Derived from Hysteresis Loops

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(Received December 16, 1978; in final form January 26, 1979)

SUMMARY

The dislocation model developed in Parts I - III is examined quantitatively. According to this model loop patches result from random trapping of glide dislocations whereby a constant fraction of them are incorporated into the loop patches in each cycle. The dislocation density in these is equilibrated rather easily because of the low friction stress on the loops in prismatic glide. As another result of the low friction against prismatic glide the loop patches adjust towards optimum dislocation density such that the stored energy is minimized. This imparts to them volume elasticity and properties similar to Taylor lattices. The back stress, which was determined in Part II from an analysis of the hysteresis loops, is identified with the maximum elastic reaction of the dislocation lattice against the imposed strain at the end of each cycle. Correlated with this is a friction stress of closely similar magnitude arising firstly because relative motions of the dislocation lattices beyond the confines of their immediate energy minima are irreversible and secondly because of the anchoring of glide dislocations at loop patch surfaces through local loop polarization. This feature explains a major experimental result of Part II, namely the equality of the friction stress and the back stress except for that part of the friction stress which can be ascribed to jog dragging and point-defect hardening. With respect to deformations within the momentary energy valley the dislocations in the loop patches respond quasi-elastically as if the elastic constant of the material was too low. The magnitude of the apparent elastic constant depends on the configuration of the dislocation lattice. Comparison with the experimentally observed quasi-elastic behavior indicates that the lattice is nearly close packed. Further, comparison with the experimentally determined dislocation density in the loop patches at saturation suggests that in all cases about 10% of the glide dislocations become trapped in the loop patches. The magnitude of the back stress and its dependence on the number of cycles and fatigue strain range derived from the model is in almost perfect agreement with observations; in fact it is well within the limits of reliability of both theory and experiment. Another check of the theory is possible via the changes in hysteresis loop shape with the number of cycles beyond the cumulative strain at which the loop patches can accommodate the fatigue strain by simple "flipping". The agreement between the predicted transformation of both stress and strain in proportion to the square root of the number of cycles and the observed changes in hysteresis loop shape was found to be excellent. These results and those of Parts II and III apply to the whole range of fatigue amplitude in the plateau region which is characterized by the formation of persistent slip bands at a stress of about 30 MPa.

1. INTRODUCTION

The general qualitative conclusions derived in Part I [1] regarding dislocation behavior in fatigued single crystals subject to a constant plastic strain amplitude in the push–pull mode were tested and refined by considering the back stress τ_B and the friction stress τ_F which arise in the sample and which can be extracted from the hysteresis loops [2]. Part II [2] was devoted to the discussion of

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EFFECTS OF SURFACE FILMS ON THE PERFORMANCE OF SILVER GRAPHITE (75 w/o Ag, 25 w/o C) ELECTRIC BRUSHES

BY

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ABSTRACT

The brush resistance of silver graphite (Stackpole SG142, 75 w/o Ag, 25 w/o C) has been investigated over a range of speeds up to 35 m/sec and a range of current densities up to $46.5 \times 10^5 \frac{A}{m^2}$. The data show conclusive evidence for the build-up and breakdown of surface films due to the graphite lubrication, and also for a persistent surface film of about 10^{-12} ohm-m^2 film resistivity. Film breakdown appears to be triggered at some critical combination of current density and speed. In the absence of the lubricating film, the brushes run at much lower electrical loss and with a reduced coefficient of friction. This result suggests that the optimum performance of the brush is at high speeds and current densities.

INTRODUCTION

The transfer of current between solids can be achieved in two basic ways; with or without the presence of deliberate lubrication at the contact interface The obvious advantage of adjuvant lubrication in limiting the frictional losses of electrical brushes is offset by a corresponding high film resistance at the electrical contacts. If no lubrication were used in conjunction with monolithic solid brushes, the very low brush load necessary to avoid high frictional losses would contribute enlarged constriction effects to their resistive behavior, or so it is generally believed.

Silver graphite composite brushes have already been studied extensively by researchers at the Westinghouse Research and Development Center.[1,2,3] Somewhat at variance with our findings, they concluded that the film contribution to the total resistance is negligible for brushes with high metal content.[4] Since these brushes are the best commercially available for high current density applications, a detailed investigation of the film behavior is necessary in order to determine as conclusively as possible to what extent lubrication at electrical contacts is advantageous.

As will be seen, the results of the present study indicate the possibility of eliminating lubricating films, thereby decreasing the contact resistance without raising the coefficient of friction.

EXPERIMENTAL PROCEDURE AND RESULTS

The Stackpole SG 142 brushes (75 w/o Ag, 25 w/o, C) were tested on an apparatus described in an earlier paper.[5] Cooling has been added by blowing test atmosphere gas over the brushes. This method is effective in reducing and stabilizing the brush bulk temperature. However, it has not been determined by how much the contact interface temperature is reduced.

The major testing conditions are summarized in Table 1. At fixed sliding speed and brush load, successively higher currents were passed through the brushes after which the current was stepwise reduced through the same sequence of values. Unless otherwise noted, the time between measurements at successive current densities was on the order of one minute.

The test results have been assembled in Figures 1-5 and Tables 2-4. Although data have been collected over a fairly extensive range of test parameters, the number of experimental variables is too high to allow for exhaustive study. Therefore, the brush tests discussed in this paper were made at a fixed brush load with sliding speeds between 5.1 m/sec and 35 m/sec and current densities between $2.3 \times 10^5 \frac{amps}{m^2}$ and $46.5 \times 10^5 \frac{amps}{m^2}$.

For the sake of brevity, this paper concentrates on the anode brush test results. The cathode brush generally

Effects of Surface Films on the Performance of Silver–Graphite (75 wt% Ag, 25 wt% C) Electric Brushes

SARA DILLICH AND DORIS KUHLMANN-WILSDORF

Abstract—The brush resistance of silver graphite (Stackpole SG142, 75 wt% Ag, 25 wt% C) has been investigated over a range of speeds up to 35 m/s and a range of current densities up to 46.5×10^5 A/m^2. The data show conclusive evidence for the buildup and breakdown of surface films due to the graphite lubrication and also for a persistent surface film of about 10^{-12} $\Omega \cdot m^2$ film resistivity. Film breakdown appears to be triggered at some critical combination of current density and speed. In the absence of the lubricating film the brushes run at much lower electrical loss and with a reduced coefficient of friction. This result suggests that the optimum performance of the brush is at high speeds and current densities.

INTRODUCTION

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TABLE I
TEST CONDITIONS

Brushes:	Stackpole Silver Graphite Composite Brushes, SG 142 (75 w/o Ag, 25 w/o C)
Brush Face Area:	0.067 in^2 = 0.43 cm^2
Brush Angle:	15° trailing
Number of Brushes:	two brushes, one positive, one negative, run on separate tracks
Brush Force:	8.3 Newtons
Rotor:	Copper 8.13 x 10^{-2} m diameter (3.2 in. diameter)
Sliding Speeds:	5.1 m/sec, 13 m/sec, 26 m/sec, 30 m/sec, 35 m/sec
Currents:	10A, 34A, 67A, 100A, 134A, 167A, 201A
Atmosphere:	ambient air when noted otherwise: humidified CO_2, 22° D.P.

Silver–graphite composite brushes have already been studied extensively by researchers at the Westinghouse Research and Development Center [1]–[3]. Somewhat at variance with our findings, they concluded that the film contribution to the total resistance is negligible for brushes with high metal content [3]. Since these brushes are the best commercially available for high-current density applications, a detailed investigation of the film behavior is necessary in order to determine as conclusively as possible to what extent lubrication at electrical contacts is advantageous. As will be seen, the results of the present study indicate the possibility of eliminating lubricating films, thereby decreasing the contact resistance without raising the coefficient of friction.

EXPERIMENTAL PROCEDURE AND RESULTS

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The major testing conditions are summarized in Table I. At fixed sliding speed and brush load successively higher currents were passed through the brushes after which the current was stepwise reduced through the same sequence of values. Unless otherwise noted, the time between measurements at successive current densities was on the order of one minute.

The test results have been assembled in Figs. 1–5 and Tables II–IV. Although data have been collected over a fairly extensive range of test parameters, the number of experimental variables is too high to allow for exhaustive study. Therefore, the brush tests discussed in this paper were made at a fixed brush load with sliding speeds between 5.1 m/s and 35 m/s and current densities between 2.3×10^5 A/m^2 and 46.5×10^5 A/m^2.

For the sake of brevity this paper concentrates on the anode brush test results. The cathode brush generally exhibited a lower voltage drop than the anode brush; otherwise its contact behavior was similar to that of the anode brush.

DISCUSSION

Contact Resistance

The total resistance per brush R_T calculated from measured values of voltage drop and current is composed of three terms: the constriction resistance R_C, the bulk resistance of the brush

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DEVELOPMENT OF HIGH-PERFORMANCE METAL FIBER BRUSHES

I - BACKGROUND AND MANUFACTURE

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ABSTRACT

On the basis of theoretical arguments, the potential improvement of metal fiber brush performance above the performance of monolithic brushes is very great. First-order theory suggests that the fiber diameter should lie between a few to perhaps one hundred microns, and the packing density between a few percent and, say, 20% at the most. Metal fiber brushes of this kind can be made by etching away the matrix material from among the fibers in filamentary materials such as are in use for superconducting devices, ultimately no doubt at modest cost. The cost of making a few small laboratory samples of the requisite multifilamentary materials by industrial processes is, however, prohibitive. Methods were therefore developed which adapt the multiple drawing and rebundling employed for superconductive multifilamentary materials to the laboratory. Brushes have so far been made with fibers of copper, gold, niobium, platinum and silver. Part II reports on their testing and properties.

INTRODUCTION

The word "brushes" for electrical current transfer between stationary and moving parts of machinery or apparatus betrays the early form of such devices, namely fiber brushes. The first relevant patent appears to be that of Thomas A. Edison[1] applied for in November 1882. There has been an impressive number of subsequent suggested improvements on "brushes," as well as related inventions which never found any significant application.

The reason for the perceived superiority of electrical fiber brushes with many separated fibers, has been well stated by Elihu Thomson[2] when he wrote in his May 21, 1895 patent application for a carbon brush: "The particular object of my invention is to improve the conductivity of the brush while preserving its elasticity and to provide a large number of contact points for the reception or delivery of current from the brush, the different parts of the brush adapting themselves by their elasticity or flexibility to surfaces which are not altogether true. Another object of my invention is to reduce to a minimum the pressure which has to be applied to the brush in order to secure sufficient contact with the commutator . . ."

The brush proposed by Elihu Thomson was already surprisingly advanced, consisting of lightly metallized carbon filaments. The widespread introduction of Edison's, Thomson's and other inventors' fiber brushes was presumably prevented by three causes. Firstly, fiber brushes tend to be much more expensive than solid, i.e. "monolithic", brushes. Secondly, the monolithic graphite brush was successively improved to the point that its losses are easily tolerable in all previously common applications, its lifetime is long, and its cost low. Thirdly, as will be shown in part II, the brush parameters (i.e., packing density, fiber diameter, brush pressure and fiber length) importantly influence brush performance, as does the ambient atmosphere. Lacking some theoretical understanding and careful experimental testing it would be difficult, to say the least, to locate optimum combinations.

During the past several years, the interest in fiber brushes has been revived on account of the development of engineering concepts and planned devices which call for very high current densities and high relative speeds, often with only small total potential differences generated, demanding much lower losses per ampere conducted than was previously permissible. The standard monolithic graphite brush cannot meet the envisaged new much more stringent requirements.

THEORETICAL BRUSH DESIGN

In its basic principle, the goal that one wants to achieve with fiber

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DEVELOPMENT OF HIGH-PERFORMANCE METAL FIBER BRUSHES

II - TESTING AND PROPERTIES

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ABSTRACT

Metal fiber brushes as described in Part I have given excellent results when tested at light loads against stationary surfaces as well as within a wide range of relative speeds. At a load between 0.1 and 0.2 N (about 0.5 oz) the static contact resistance against a clean, polished copper surface was ~ $1.6 \times 10^{-4}\ \Omega$ for a surface of ~ 0.1 $in^2 \approx 0.7\ cm^2$. When the brushes are run in an argon atmosphere they exhibit a constant contact resistance of a few tenths of a milliohm at speeds up to 35 m/sec and current densities up to $6.5 \times 10^6 A/m^2 \approx 4000$ A/in^2, which were the limits of testing capability. Under the most favorable conditions located yet, namely a brush pressure of several thousand N/m^2, a copper rotor with a gold - carbon surface treatment, and a moist argon atmosphere, the sum of mechanical and electrical loss at 6.5×10^6 A/m^2 and 35 m/sec amounted to ~ 0.1 watt per ampere conducted per brush. This is much superior to the performance of the best commercially available brushes. The relative performance advantage of the brushes is equally large at low current density and low speeds, as for stationary contacts at low loads. The results are fully understood on the basis of contact theory. These findings promise a significant advance in brush and contact technology.

INTRODUCTION

Metal fiber brushes, with fiber diameters from a few microns to 120 μm, and packing densities between a few % and up to 20%, have been made of various materials by the method discussed in part I. They were tested using apparatus described previously[1] improved by the inclusion of a modified brush holder and loading device.

In the improved device, rather than monitoring the position of the brush relative to the rotor by means of a linear differential transducer and reading the compression of the loading spring by eye, the transducer is employed to monitor the compression of the spring, thereby achieving a much more accurate load determination. By advancing the brush via a micrometer head so as to keep the spring compression, and hence the load, constant, the brush wear may be determined continuously to the reading accuracy of the micrometer head. Further, the linear bearings guiding the brushes have been replaced by one pair each of the best linear bearings available. With these improvements, the apparatus is now easily adequate to all reasonable requirements.

Brushes with gold, platinum, niobium and copper fibers have been tested, - the latter two kinds only very sketchily. Since the most complete and systematic set of data available so far has been obtained with gold fiber brushes, these shall be discussed primarily. Throughout, great care was taken to achieve the greatest possible degree of reproducibility by observing well-defined and clean experimental conditions. Measurements were made in relatively dry (humidity somewhat below 30%) and moist (humidity somewhat above 80%) argon, and in two load ranges, namely loads under which the brushes did not suffer significant permanent deformation as macroscopically observable, and loads which caused distinct plastic deformation of the brushes. As will become clear later in this paper, the behavior of the individual a-spots is elastic in both cases, however.

NEW DEVELOPMENTS and APPLICATIONS IN COMPOSITES

KUHLMANN-WILSDORF
HARRIGAN

NEW DEVELOPMENTS and APPLICATIONS IN COMPOSITES

Edited by
DORIS KUHLMANN-WILSDORF
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CONFERENCE PROCEEDINGS

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A mechanism for the origin of screw dislocation sequences, giant screw dislocations, and polytypism in platelet crystals

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ABSTRACT

Several workers have observed growth spirals of very large step heights on platelet crystals, sometimes associated with polytypism. These are attributed to spiral growth round a sequence of similar screw dislocations in a close planar array or a single giant screw dislocation. Polytypism can be (but is not necessarily) caused by such giant growth steps. The origin of the dislocations giving rise to them has remained obscure. *It is proposed that they are due to radial impurity gradients* which cause the lattice parameter to change gradually away from the centre. The hoop stresses which thus arise may be relieved by elastic buckling, twinning, glide or brittle fracture. Since the hoop stresses produce no shear on either the basal plane or the prismatic planes of a crystal growing parallel to the basal plane, as long as the crystal remains planar, the hoop stresses may build up until the platelet buckles, cracks or twins, if those are the only active slip planes in the material. In all cases the dislocations which are formed in glide will be near the screw orientation and slip will be concentrated on or close to those planes which first began to glide. Therefore, if the slip has a component along the relevant axis that is comparable to or larger than the platelet thickness, it will lead to fracture. If the glide has relieved the hoop stresses before that point, it will cease. In the first case, the two edges of the crack will continue to move forward by independent crystal growth and are liable to give rise to growth steps of height equal to the platelet thickness at the point of fracture. Otherwise, the dislocations will crowd together near the head of the slip line which is forming and will also give rise to a giant growth step centred, however, not on a single giant dislocation but on a planar array of screw dislocations. A simple theory shows that the conditions for the proposed mechanisms must be prevalent. Experimental observations are generally in support of the theory.

§ 1. INTRODUCTION

Growth spirals of very large step heights have been observed on platelet crystals of several materials, such as SiC (Verma 1951, Amelinckx 1951), mica (Baronnet 1972), CdI_2, PbI_2 (Forty 1954), haematite (Sunagawa 1962), rare-earth orthoferrites (Tolksdorf and Welz 1972) and electrodeposited silver

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Materials Science and Engineering, 46 (1980) 209 - 219

Dislocation Behavior in Fatigue
V: Breakdown of Loop Patches and Formation of Persistent Slip Bands and of Dislocation Cells

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(Received February 14, 1980; in revised form April 10, 1980)

SUMMARY

*The loop patch and channel structure in fatigued copper becomes unstable at a resolved shear stress of about 30 MPa at room temperature and is replaced by persistent slip bands (PSBs). This instability depends little, if at all, on frequency of cycling and strain amplitude. It appears to be a function only of the dislocation density in the loop patches but includes a temperature dependence (*i.e. *the critical stress rises to about 70 MPa at 4 K) which suggests that cross-slip, defect dragging and/or "forest cutting" are involved.*

In view of the available evidence it is suggested that the discussed instability is due to secondary glide on systems intersecting the primary slip plane which, through moving primary edge dislocations normal to their slip planes, permits their mutual annihilation. It is envisaged that such secondary glide takes place on a small scale in a very large number of places in the loop patches once the critical dislocation density is reached.

A semiquantitative analysis of the stresses involved in conjunction with micrographical evidence indicates that the intersecting glide occurs at least partly on cube planes. If this interpretation is correct, the removal of the primary loops leaves behind dislocations which are faulted but are fairly mobile and are liable to annihilate each other mutually to a large extent and to leave "debris" which is then swept into the dipolar walls in the PSBs, all in agreement with micrographical evidence.

Cell formation in the PSBs is believed to result at stresses high enough to introduce secondary glide in the PSBs.

Loop patches, consisting as they do of mobile dislocations, must be attracted to the surfaces on account of the (mild) dislocation surpluses at their boundaries with the channels and the image forces arising therefrom. Such image forces are virtually independent of the presence of thin surface films, but such surface films can inhibit the escape of the prismatic loops out of the metal. Correspondingly, loop patches will be either enriched or depleted at surfaces, to a depth comparable with the average loop patch diameter, depending on whether the surface films are or are not so thick as to bar the egress of the loops. One probable example of each case is discussed.

1. INTRODUCTION

In constant-amplitude plastic strain push–pull fatigue of copper single crystals at room temperature, persistent slip bands (PSBs) begin to form out of the loop patch and channel structure when the applied resolved shear stress has reached about 30 MPa on the primary slip system. This value depends little, if at all, on the strain amplitude within the PSB range and rate of cycling and therefore appears to be triggered at a critical loop density.

In Parts I - IV [1 - 4] the dislocation motions and associated stresses up to the point at which the PSBs begin to form have been investigated. Further, in Part I [1] the motions of the glide dislocations in PSBs and some basic properties of the PSBs were also examined. It is necessary to return once more to the question of PSB formation, however, because of recent experimental evidence [5] indicating that the transformation of the loop patches into PSBs need not be catastrophic as had initially been assumed [1] but can (and typically appears to) take place gradually and continuously.

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DEVELOPMENT OF HIGH-PERFORMANCE METAL FIBER BRUSHES

III - FURTHER TESTS AND THEORETICAL EVALUATION

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ABSTRACT

Fiber brushes of different metals, with fiber diameters between 6.6 and 100 microns and packing fractions between 2.9% and about 20% have been tested. Their behavior was found to be in accord with theory. The brushes exhibit very superior performance as compared to monolithic brushes. When properly constructed and loaded, the metal fiber brushes can be used to at least 72 m/s speed and with current densities of 6.5 MA/m^2, i.e. 4200 A/in^2. On account of their very large number of a-spots, the brushes have very low "noise".

INTRODUCTION

In the preceding two parts of this series[1,2], subsequently referred to as parts I and II, we have reported the development of a new type of electrical brush consisting of a "velvet" of fine metal fibers protruding from a metal matrix. Such brushes combine high compliance in the direction normal to the contacting surface with a very high number of a-spots. Correspondingly, the brushes can, and typically should, be run at much lower pressures than used for monolithic brushes, even while their electrical resistance is much lower.

Experiments carried out over the past year have expanded the range of metal fiber brushes made and tested. These have led to an increasing confidence in the future technological applicability of metal fiber brushes in a wide range of tasks and circumstances.

According to part II, the resistance of a metal fiber brush of overall geometrical area A_B of the running surface, at brush pressure p_B, is

$$R_B A_B = \Delta V/J = (\sigma_F/K^2)[E^2 d^2/(p_B{}^2 r_c{}^2 70\alpha f)]^{1/3} \quad (1)$$

wherein, from eqs. 5, 6, 8, 10b and 19 of part II,

$$K^2 = 1 + 2(r_c s^3/d^4)^{1/3}(\alpha f E/p_B)^{2/3}, \quad (2)$$

provided that the deformation at the a-spots is elastic, at least after an initial period of "running in."

Here, ΔV is the voltage drop across the brush when the current density, $J = I/A_B$, is passed through it. Further, σ_F is the film resistivity of the surface film between the metal of the fibers and of the contacting metal at the a-spots, d is the fiber diameter and f, the packing fraction, is the cross sectional area of all fibers together compared to the brush area A_B. Next, α designates the number of a-spots per fiber, r_c the surface curvature at the a-spots, and E the pertinent weighted average of Young's modulus (a function of the two E-moduli as well as Poisson's ratios and surface curvatures; see R. Holm, Electric Contacts, Appendix I.) Finally, s is the maximum gap width for effective electron tunneling.

The underlying considerations leading to eqs. 1 and 2 are these: Both the ohmic fiber resistance and a-spot resistance are negligible so that the brush resistance is controlled by the surface film that is always present. However, due to the large number of a-spots, the a-spot radius is very small compared to the radius of surface curvature, and tunneling through the annular area about the load-bearing part of the a-spots (of radius r_b) makes a significant contribution to the conductivity. The factor K^2 is the ratio of the current carrying area to the load bearing area of the a-spots.

In part II, measurements of three different gold fiber brushes were utilized to determine values for the otherwise unknown parameters in the theory, including σ_F, α, s and r_c. With a total of four independent measurements available, a unique set of values could be derived for these parameters, and these matched the brush resistances for the same brushes in the stationary condition, on the assumption that the number of a-spots per fiber was unity with the brushes running but three when at rest. This was considered to be reasonable on the argument that the small forces acting on the individual fibers could not effect the requisite very rapid flexing motions that would be required to constantly align the end surfaces of the fibers with the local contact surface when running, but these forces where sufficient to keep the fibers in contact with that surface throughout.

Also evidence for the action of aerodynamic lift was found. This expresses itself in a slowly rising value of the brush resistance with brush velocity which is the more pronounced the thinner the fibers and the smaller the brush load. At a brush pressure of about eight kN/m^2, the effect is slight up to about one quarter of the speed of sound.

Interestingly, the surface radius of curvature, r_c, was found equal to the fiber radius. This prompted the thought that the actual surfaces in contact were smoother than corresponding to $r_c = d/2$ but that, at best, the fiber ends would have much the same mechanical effect on the opposing surface as a sphere indenter of a diameter equal to the fiber diameter. Correspondingly, it was assumed

MEASUREMENT AND SIGNIFICANCE OF ROTOR TEMPERATURE DURING BRUSH TESTING

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ABSTRACT

A novel method for measuring the temperature of the slip ring during brush testing was developed and was used inside a brush testing chamber for the accurate measurement of slip ring (rotor) temperatures during silver graphite Stackpole (SG 142, 75 w/o Ag, 25 w/o C) electric brush tests. Additionally, a new simple method of cooling brushes during testing was devised consisting of a squirrel cage fan rigidly connected to the rotor. The silver graphite brushes displayed reduced electrical losses with increasing temperature, apparently because the film resistivity is a unique function of rotor temperature. Analysis of the data suggests that the film resistance at the interface is controlled by a Cu_2O layer which exhibits electrical resistance behavior characteristic of a semiconductor with an energy gap for intrinsic current conduction of 1.7 ev.

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HOLM CONFERENCE ON ELECTRICAL CONTACTS
Pages 141-149

INTRODUCTION

Temperatures of brush - slip ring interfaces are of considerable practical as well as theoretical interest, since they influence brush performance and are an important input parameter in the theoretical evaluation of sliding contact phenomena.[1,2] Yet, they are generally known only quite imprecisely, to some considerable extent because accurate temperature measurements of moving or rotating pieces of machinery pose a perennial problem. For low temperatures pyrometric methods cannot be used, or are prohibitively expensive. The use of embedded thermocouples is also unsatisfactory, principally because of the need for a fixed reference temperature and because of the low voltage output. Namely, motion or rotation inhibits the use of thermocouple leads without intermediate sliding contacts. Moreover, the thermocouple output is typically rather less than the voltage drop across a sliding contact and the associated noise. With the use of the best available metal fiber brushes[3,4] these problems are greatly reduced but not entirely eliminated; besides, sliding contacts themselves produce heat and are thus prone to introduce spurious thermovoltages.

In order to overcome these difficulties the following method was developed, specifically to measure slip ring (i.e. rotor) temperatures during brush testing. It allows measurements of bulk rotor temperature without any accompanying interference with the brush testing procedure. The system includes one semiconductor sensor per location at which the temperature shall be monitored. These sensors are embedded in the rotor.

In the present study, integrated circuit temperature transducers (Analog Devices 590) have been used as sensors, however thermistors would presumably serve equally well. Two similar transducers were used in the rotor in order to test the consistency of the temperature measurement.

The temperature measurement assembly was used to clarify two aspects of great interest to current brush research: (i) to determine the effect of an auxiliary cooling system in the brush testing rig, described in a previous paper[5], and (ii) to determine the effect of rotor temperature on the performance of Stackpole SG 142 (75 w/o Ag, 25 w/o C) silver graphite brushes which have been the object of previous investigation.[6] As described

D. Wilsdorf - filed June 5 1980
Serial # 156,630

TITLE OF THE INVENTION

"A VERSATILE ELECTRICAL FIBER BRUSH AND METHOD OF MAKING"

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to an electrical brush for making electrical connection to one or more objects, often but not necessarily having predetermined shape and predetermined orientation relative to the brush, such as a slip ring in a motor or electrical generator, a brush holding device, and/or a stationary contact in a switch. This invention also relates to methods of making such an electrical brush.

Description of the Prior Art

Electrical brushes for utilization in electrical applications have long been known in the prior art. Perhaps the earliest modern electrical brush was disclosed by Edison in U.S. Patent No. 276,233, which resulted in numerous suggested improvements on electrical brushes, as well as related inventions which have otherwise never found significant applicaton.

Thomson, in U.S. Patent N. 539,454, recognized various advantages of electrical brushes constructed of plural lightly metalized carbon filaments, and in particular the improved brush conductivity, elasticity and reduced mechanical and electrical resistance thereby provided.

More modern development of electrical brushes is evidenced in U.S. Patent 3,668,451 to McNab and U.S. Patent 3,821,024 to Wilkin et al. In the McNab patent is disclosed an electrical brush formed of refractory non-conducting fibers, each of which has deposited thereon a metal film on the surface there-

D. Wilsdorf, C. M. Adkins and H. G. F. Wilsdorf, filed April 9, 1980 Serial # 138,716

TITLE OF THE INVENTION

"AN ELECTRIC BRUSH AND METHOD OF MAKING"

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to an electrical brush for making electrical connection to an object having a predetermined shape and a predetermined orientation relative to the brush, such as a slip ring in a motor or electrical generator, or a stationary contact in a switch. This invention also relates to a method of making such an electrical brush.

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Fundamentals of Friction and Wear of Materials

Papers presented at the
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pp. 119 - 186

Dislocation Concepts in Friction and Wear

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Abstract

Using dislocation concepts, primarily as relevant to geometrical considerations, and other basic facts concerning plastic properties of crystalline materials, a number of qualitative and quantitative relationships in the area of friction and wear are developed:

(1) The accepted model for friction and wear is expanded to include the micro-roughness which must necessarily arise at contact spots on account of inhomogeneities in elastic and plastic deformation.

(2) A simple formula is proposed to describe the conditions under which adhesion is important.

(3) The concept of the "basic" case is introduced, which is sliding wear between average-rough and average-clean surfaces such that adhesion as well as surface films can be neglected.

(4) A closer examination of the deformation processes at indentations and underneath wear tracks shows that the reactive force balancing the normal force between the two sliding surfaces originates at considerably larger distances from the interface than the reaction to the tangential traction.

(5) Based on this insight, an expression for the coefficient of friction in the "basic" case is derived. This is found to predict decreasing values of the coefficient of friction with decreasing crystal symmetry and, hence, decreasing numbers of "easy" crystallographic glide systems.

(6) This expression for the coefficient of friction predicts a number of effects which appear to be consistent with observations, including dependence on surface textures, surface hardness, and surface temperature.

(7) The conditions under which surface films may be neglected are more closely examined, together with some effects of surface platings.

(8) Delamination wear is found to follow necessarily whenever the flow-stress of the material near the surface is a function of the cumulative strain.

(9) Expressions for the wear coefficient and for the incubation period preceding "steady state" delamination wear are derived and compared with available data.

Materials Science and Engineering, 51 (1981) 31 - 37

Glide and Climb Stresses on Secondary Slip Systems in F.C.C. Crystals Due to Isolated Primary Edge and Screw Dislocations

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(Received April 11, 1981)

SUMMARY

The climb and glide stresses resulting from an isolated $\frac{1}{2}[\bar{1}01](111)$ *edge dislocation as well as from an isolated* $\frac{1}{2}[\bar{1}01]$ *screw dislocation were calculated for all possible* $\langle 110\rangle\{111\}$ *and* $\langle 110\rangle\{100\}$ *slip systems. Knowledge of these stresses is needed in studies of glide on non-primary slip systems as affected by agglomerations of primary dislocations, especially pile-ups, or the loop patches and dipolar walls observed in fatigued specimens. The same data are believed also to be highly applicable to fracture studies in that the stresses about a mode I crack resemble those of a set of edge dislocations along the crack edge with their Burgers vectors normal to the plane of the crack. Similarly, a mode II crack may be simulated by an edge dislocation whose Burgers vector lies in the plane of the crack normal to the crack edge, and a mode III crack may be simulated by a screw dislocation.*

1. INTRODUCTION

Occasionally it is of considerable interest to know the stresses caused in non-primary glide systems by the presence of primary dislocations. Examples are problems involving the stresses of dislocation pile-ups or of the loop patches and dipolar walls formed by primary dislocations during fatigue [1]. However, it appears that this information is not available in the literature. In the present paper we aim to fill this gap by presenting the glide and climb stresses caused in all the possible $\langle 110\rangle\{111\}$ and $\langle 110\rangle\{100\}$ slip systems by the presence of an isolated $\frac{1}{2}\langle 101\rangle\{111\}$ dislocation, *i.e.* a CA(d) dislocation using the geometry of Fig. 1.

The calculations were made using the stress components of edge and screw dislocations available in the literature, *e.g.* in ref. 2, and resolving them into the corresponding orientations on a cylinder of radius R about the dislocation axis. The climb stresses are found as the normal stress components parallel to the six different $\langle 110\rangle$ glide directions, and the glide stresses are determined as the dislocation stresses resolved into all possible combinations of $\langle 110\rangle$ glide directions and their $\{111\}$ or $\{100\}$ glide planes. The calculations were made for both an isolated CA(d) edge dislocation and an isolated right-handed CA screw dislocation, so as to allow us to deduce the general case from the appropriate superimposition of these two cases in order to generate the results for arbitrarily mixed primary dislocations. The data are obtained in units of $Gb/2\pi(1-\nu)R$ for the CA(d) edge dislocation and in units of $Gb/2\pi R$ for the CA screw dislocation.

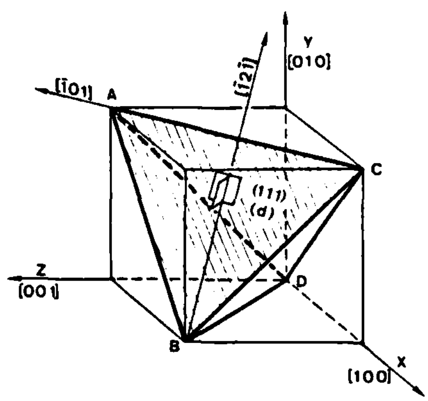

Fig. 1. The axis orientations, Thompson tetrahedron and indexing used in this paper. The notation follows the usual one for the Thompson tetrahedron. The cube planes are indicated as follows: (x) = (100); (y) = (010); (z) = (001).

0025-5416/81/0000-0000/$02.50

Wear, *71* (1981) 119 - 125

Short Communication

Device for the control and measurement of brush forces to an accuracy of a few grams-force while monitoring brush resistance and brush wear at currents up to 500 A or more

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(Received May 18, 1981)

A brush holder is described which permits the electrical performance of a brush to be tested under currents of up to at least 500 A and speeds of up to at least 70 m s^{-1} and under brush forces that can be applied and maintained within close limits. Simultaneously, the brush wear can be monitored continuously.

1. Introduction

The development and testing of electrical brushes requires equipment which permits simultaneous control and measurement of the brush load and current while the brush is operated within a wide range of speeds. In the case of high performance brushes, which are designed to carry currents of up to several hundred amperes per square centimeter under brush pressures as small as 10 gf cm^{-2}, these requirements are difficult to fulfill. The following brush holder was designed to meet this need. It is a modified version of the brush holder used in the brush-testing apparatus described by Srikrishnan *et al.* [1] and may be used for the testing of metal fiber brushes [2, 3] as well as monolithic brushes. Brush forces have been maintained and measured to an accuracy better than 3 gf while the brushes were subjected to currents at the limit of present generating capacity, namely 500 A, at speeds up to the present apparatus limit of about 70 m s^{-1}.

2. Description of the brush holder

A schematic section of the brush holder is shown in Fig. 1. The overall length of the holder is about 30 cm. It is adjustably but firmly attached to the back plate of the brush-testing apparatus. The back plate serves as the support not only for the brush holders and positioning devices etc. but also for the enclosure within which testing is done, under protective or other atmospheres if so desired. The ends of the two horizontal symmetrically arranged brush holders of the apparatus [1] project out of the side walls of

Materials Science and Engineering, 50 (1981) 127 - 136

Dislocation Behavior in Fatigue

VI: Variation in the Localization of Strain in Persistent Slip Bands

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(Received March 27, 1981)

SUMMARY

It is now widely accepted that the strain localized in the persistent slip bands (PSBs) of fatigued pure metals is about 0.01, so much so that the average nature of this strain appears to have been forgotten. Accordingly, we offer interferometric observations on the details of slip offsets within PSBs. These were obtained by repolishing the gauge surfaces of specimens cycled into saturation and restraining to the strain amplitude; they thus represent PSB behavior in transitu. Strain concentrations up to 1000 are shown to exist at the surface well into saturation. The implications of these results for understanding dislocation behavior in fatigue are discussed: the slip step behavior can be explained by the glide of groups of like-handed screw dislocations in the PSBs and is not consistent with a model in which any significant part of the strain is due to edge dislocations bowing out of the PSB walls.

1. INTRODUCTION

By observing the fraction of the gauge surface of a fatigued single crystal which was occupied by persistent slip bands (PSBs) Winter concluded that the strain carried by a PSB is about 0.01 [1, 2]. Winter observed the PSBs from the start of cycling and thus the measurement of strain localization was based on the integrated effect of all the cycling. Finney and Laird [3], however, who used interferometry on specular specimens periodically repolished during cycling, measured the localized strain at a *given point in life*. They confirmed that the localized strain was about 0.01 (actually shear strain amplitude equals 0.006 25), but this was an average value. Since then, the value of 0.01 has acquired the inflexibility expected of the velocity of light, and its average nature appears to have been overlooked [4].

Since attempts to understand cyclic deformation require a realistic values (or values) of the localized strain [5 - 9] and since fatigue cracks are initiated in PSBs, almost certainly as a result of the notch peak topography due to strain irreversibility, quantitative values of the variation in strain localization are also needed. The purpose of the present paper is to demonstrate the degree of localization observed in copper single crystals oriented for single slip, to give some idea of the numbers of dislocations involved in the volumes of concentrated plastic strain and to explore dislocation behavior with reference to interferometric observations.

2. EXPERIMENTAL DETAILS

The results to be reported here were obtained in the same investigation as that reported by Finney and Laird [3] but were not reported then because of the need for concise publication. Thus the exper-

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DEVELOPMENT OF ELECTRIC FOIL BRUSHES

A Thesis

Presented to

the Faculty of the School of Engineering and Applied Science

University of Virginia

In Partial Fulfillment

of the Requirements for the Degree

Master of Science (Materials Science)

by

Paul B. Haney

May 1981

PCT INTERNATIONAL APPLICATION TRANSMITTAL LETTER	DATE: June 5, 1981
REGARDING THE INTERNATIONAL APPLICATION OF University of Virginia Alumni Patent Foundation	DOCKET OR REFERENCE NUMBER 494-044-2 PCT

ENTITLED
A VERSATILE ELECTRICAL FIBER BRUSH AND METHOD OF MAKING

To the United States Receiving Office (RO/US):

Accompanying this transmittal letter is the above-identified International application, including a completed request form (PCT/RO/101). Please process the application according to the provisions of the Patent Cooperation Treaty.

The following requests are made of the RO/US:

1. [X] CERTIFIED COPY PREPARATION—Please prepare a certified copy of the priority document for the above-identified International application and transmit the certified copy to the International Bureau according to the provisions of 37 CFR 1.451.

IDENTIFICATION OF PRIORITY DOCUMENT	U.S. SERIAL NUMBER	U.S. FILING DATE	APPLICANT
	156,630	5 June 1980	University of Virginia Alumni Patent Foundation

To cover the cost of copy preparation and certification,

[X] a (check) (money order) in the amount of $ 1,261.00 is attached to this transmittal letter.

[X] the RO/US is hereby authorized to charge the following deposit account no.: 15-0030.

2. [ ] ALTERNATE TRANSMITTAL OF RECORD COPY—As the accompanying International application is being filed within 11 months of the claimed priority date, according to the provisions of 37 CFR 1.461,

[ ] hold the Record Copy available for pickup by 10 days before the expiration of 13 months from the claimed priority date in room 2-4C08, Crystal Plaza, Arlington, VA.

[ ] mail the Record Copy to me by 15 days before the expiration of 13 months from the priority date.

3. [X] SUPPLEMENTAL SEARCH FEES—Please charge any Supplemental Search fees that may be required by the United States International Searching Authority (ISA/US) to deposit account no.: 15-0030.

I understand that this authorization is subject to my oral confirmation thereof in each instance and that it in no way limits my right to submit a protest against payment of the Supplemental Search fees, but is merely an administrative aid to assure that the ISA/US may timely complete the Search Report.

4. [X] REFUND OF SEARCH FEES/SUPPLEMENTAL SEARCH FEES—If the ISA/US determines that a refund or reimbursement of the Search fee and/or any Supplemental Search fees is warranted due to the benefit of a prior search, or due to a decision that applicant's protest is justified, such refund is

[ ] to be in the form of a U.S. Treasury check.

[X] authorized to be credited to the following deposit account no.: 15-0030.

5. [X] DISCLOSURE INFORMATION—In order to assist in screening the accompanying International application for purposes of determining whether a license for foreign transmittal should and could be granted and for other purposes, the following information is supplied:

A. [ ] There is no prior filed application relating to this invention.

B. [X] There is a prior application, serial number 156,630 filed on June 5, 1980 which contains subject matter that is

1. [ ] substantially identical to that of the accompanying International application.

2. [X] less than that of the accompanying International application. The additional subject matter of the International application appears on page(s) and ~~XXXX~~ 11,43,44,96,97 & 98.

3. [ ] more than that of the accompanying International application.

C. [ ] Disclosure information cannot be covered by the language of Points 5A or 5B above due to the involvement of several prior applications or for other reasons. A separate sheet on which the disclosure information is explained is attached to this transmittal letter.

6. [ ] REQUEST FOR FOREIGN TRANSMITTAL LICENSE—According to the provisions of 35 U.S.C. 184 and 37 CFR 5.11, a license to transmit the accompanying International application to foreign agencies or international authorities is hereby requested.

SIGNER IS THE:	NAME OF SIGNER (typed)
[ ] APPLICANT	Marvin J. Spivak
[ ] COMMON REPRESENTATIVE	SIGNATURE
[X] (ATTORNEY) (AGENT) REG. NO. 24,913	

PHILOSOPHICAL MAGAZINE A, 1981, VOL. 44, No. 6, 1351–1361

Configurations of {100} dislocation walls formed during fatigue

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[Received 3 June 1981 and accepted 18 June 1981]

ABSTRACT

The microstructure observed in a Cu–Ni alloy fatigued in multiple glide consists of two sets of similar dipolar walls parallel to two different {100} planes. These are spaced approximately 0·5 μm apart within each set but are arranged in a non-random manner in that L-joints and T-joints among the walls are much more frequent than statistically expected. It is suggested that this occurs on account of the screening of stresses at wall ends and/or the reduction of elastic constants within the walls.

§ 1. INTRODUCTION

The arrangements of dislocations in face-centred cubic crystals, orientated for single slip and fatigued to saturation, have been studied in detail, using transmission electron microscopy, by a number of workers. This work has recently been reviewed by Mughrabi (1979) and Laird (1979). Within the persistent slip bands (PSBs) which are a ubiquitous feature, the dislocations are arranged in walls perpendicular to the primary slip plane and direction. These observations have been interpreted in terms of dipolar walls of edge dislocations with short dislocation loops within and between the walls, including mechanisms accounting for the formation of the walls, their average rather uniform spacing, and the shape of the hysteresis loops (Kuhlmann-Wilsdorf and Laird 1977, 1979, Kuhlmann-Wilsdorf 1979 a, b, c).

When more than one slip system is operative during the fatigue of f.c.c. metals more complex dislocation structures have been observed, including structures consisting of two sets of mutually perpendicular walls (Rajan, Ramaswami and Sastry 1975, Rasmussen and Pedersen 1980, Charsley 1981). It has recently been shown (Charsley 1981) that these walls may be parallel to {100} and in that case can be formed through the operation of two slip systems. In the particular example investigated two Burgers vectors are involved, both in the formation of each set of walls, and the sum of the two Burgers vectors can be normal to each of the two sets of walls, with an appropriate choice of signs (see Charsley 1981, fig. 3). It is, therefore, possible to interpret the observed configurations as mutually perpendicular walls constructed from edge dislocation dipoles with mutually perpendicular Burgers vectors.

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PRODUCTION AND PERFORMANCE OF METAL FOIL BRUSHES

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Summary

Electrical brushes which were made of silver, copper and aluminum foils of 12.5 and 25 μm thickness and were composed of 15 - 195 individual foils, were tested in purified argon on a polished copper rotor at a speed of 13 m s^{-1}. Brush pressures varied between 3.1×10^3 and 2.8×10^4 N m^{-2} and current densities were up to about 700 A cm^{-2} (about 4500 A in^{-2}).

The observed dependence of the voltage drop across the brushes as a function of the current densities agreed closely with Holm's contact theory as applied to foil brushes. The film resistivities were found to be near $\sigma_F = 10^{-12}$ Ω m^2 for copper and silver and to be about 3×10^{-12} Ω m^2 for aluminum. The projected performance of foil brushes based on these results is very favorable and the future commercial use of foil brushes appears to be possible.

The total loss, electrical and mechanical, through the brushes is independent of current density if the brush pressure is chosen to minimize the total loss. If so, the loss depends only on the brush speed, the hardness of the softer of the two materials involved (*i.e.* of foil and rotor or slip ring), the coefficient of friction and the film resistivity.

Microscopic surface examinations of rotor and brushes show that the brush surface is smoothed through running the brush, whereas the rotor remains almost unaffected or is mildly roughened, as long as no arcing takes place. Arcing causes considerable surface roughening on both the brush and the rotor surface and debris is thus deposited on the rotor; this can score the brushes. Further experiments are required to determine the rate of brush wear.

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1. Introduction

The electrical resistance of electric brushes is composed of three parts: R_O, the ohmic resistance of the brush body; R_C, the so-called constriction

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Zur Größe des Reibungskoeffizienten mit und ohne Adhäsion

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Gewidmet Herrn Professor Dr. phil. Dr.-Ing. E. h. Werner Köster zu seinem 85. Geburtstag

Die oft relativ abrupte zwei- bis vierfache Zunahme des Reibungskoeffizienten bei steigender Normalkraft wird untersucht. Laut Adhäsionstheorie soll bei niedrigem Druck die relative Gleitung in Oberflächenfilmen stattfinden, während bei höherem Druck Kaltverschweißungen auftreten und Scherung unter den Kontaktpunkten erzwingen. Elektrische Messungen widersprechen dieser Theorie. Es wird stattdessen vorgeschlagen, daß bei Trockenreibung die Gleitung immer unter den Kontaktpunkten stattfindet, daß aber bei niedrigem Reibungsdruck die Kontaktpunkte einzeln operieren, während sie sich bei Auftreten von Kaltverschweißungen zu Gruppen zusammenfinden. Die Erhöhung des Reibungskoeffizienten ist eine Folge solcher Gruppierung, unabhängig davon, ob sie durch Kaltverschweißung erfolgt oder nicht. Es werden Vorschläge zur experimentellen Prüfung dieser Hypothese gemacht.

On the Magnitude of the Coefficient of Friction with and without Adhesion

The frequently observed, fairly abrupt two- to fourfold increase of the coefficient of friction with rising pressure is investigated. According to the adhesion theory, this occurs when coldwelding enforces subsurface shear below contact spots, whereas at low pressures the relative movement supposedly occurs in surface films. Electrical measurements are incompatible with this theory. Instead it is proposed that in dry sliding the relative shear always takes place below the contact spots, but that these form interacting groups when coldwelding sets in. The increase of the coefficient of friction is believed to result from such grouping, whether or not it is triggered by coldwelding. Proposals are made for the experimental testing of this hypothesis.

Die beiden wichtigsten Gesetze der Reibung, nämlich daß der Reibungskoeffizient in erster Näherung sowohl unabhängig von der Größe der geometrischen Kontaktfläche A_g, als auch von der Last ist, werden ganz allgemein darauf zurückgeführt[1])[2])[3]), daß bei allen Belastungsdrucken, die genügend weit unterhalb der makroskopischen Festigkeit des Materials liegen, atomistische Berührung nur auf der viel kleineren Gesamtfläche A_b stattfindet, die jedoch plastisch verformt wird, und zwar etwa bis zur Sättigungshärte H des weicheren der beiden sich berührenden Objekte. Die atomistische Kontaktfläche A_b besteht wiederum aus n Kontaktpunkten mit der durchschnittlichen Ausdehnung $a_b = A_b/n$. Somit ist deren durchschnittlicher Durchmesser d etwa

$$d = \sqrt{A_b/n} \tag{1}$$

wobei A_b durch die Härte H bestimmt ist. Wenn man einfachheitshalber H als den mittleren Normaldruck über einem Kugeleindruck definiert, wenn das Material bis zur Sättigung verfestigt worden ist, so ist

$$A_b = F_n/\zeta H \tag{2}$$

mit der Kraft F_n, mit denen die beiden reibenden Objekte zusammengepreßt werden, und einem Faktor ζ, der zwischen etwa 0,1 und 1 variieren kann[2]), aber meistens nahe bei 1 liegt.

Wird die Tangentialkraft, welche zur relativen Gleitung zwischen den beiden reibenden Objekten nötig ist, mit F_t bezeichnet, ist der Reibungskoeffizient μ gegeben durch

$$\mu = F_t/F_n = F_t/\zeta A_b H \tag{3}$$

was spätestens nach dem Einlaufen in

$$\mu = F_t/A_b H \tag{4}$$

übergegangen ist. Wenn also μ unabhängig von F_t gefunden wird, dann bedeutet das, daß F_t proportional zu A_b ist, da ja H eine Materialkonstante ist. Praktisch jedes Modell, bei dem relative Scherung nur an begrenzten Kontaktpunkten stattfindet, ergibt diese Proportionalität, und zwar unabhängig davon, ob diese Scherung im Material selbst, in Oberflächenfilmen, oder in einer etwaigen absichtlich eingeführten Schmierung stattfindet. Die wesentliche Frage, die es zu beantworten gilt, ist demnach, wo mikroskopisch gesehen die relative Scherung stattfindet, da diese den mechanischen Widerstand gegen die Gleitung und damit die Größe des Reibungskoeffizienten bestimmt.

Verbessertes Modell zur Reibung ohne Adhäsion

Kürzlich ist ein verbessertes Modell der Reibung vorgeschlagen worden[4]), welches verschiedene Einwände gegen die bisher gängige Adhäsionstheorie[1])[3]) in Rechnung stellt. Dieses ist in Bild 1c schematisch dargestellt, im Vergleich mit dem Adhäsionsmodell (Bild 1a) und dem „Durchpflügungsmodell" (Bild 1b). Im neuen Modell ist die Adhäsion durch Kaltverschweißung ersetzt worden durch mechansche Verhakung durch Mikrorauhigkeit. Es beruht auf der Einsicht, daß atomistische Kontaktflächen zwischen zwei Oberflächen niemals glatt bleiben können: Verformung durch Versetzungen ist meistens inhomogen verteilt und erzeugt Gleitlinien auf die Oberfläche. Wenn Verzwillingung eintritt, ist die Verformung noch inhomogener. Weiterhin sind alle kristallinen Materiale elastisch inhomogen, was bei gleichmäßigem Oberflächendruck zwischen Vielkristallen an jeder Korngrenze zu abrupten Niveauänderungen führen muß.

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ELECTRICAL CONTACT BEHAVIOR OF
SILVER-GRAPHITE (75 wt% Ag) BRUSHES

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LOW-ENERGY DISLOCATION CELL STRUCTURES PRODUCED BY CROSS-SLIP

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Computer calculations have shown that a dislocation arrangement which has a particularly low strain energy (per unit length of dislocation line) is a distinctive three-dimensional checkerboard pattern of parallelepipedal cells with a common axis of relative misorientation (1). In this arrangement cell walls (more or less) at right angles to the rotation axis are (essentially) twist boundaries. Cell walls (more or less) parallel to this axis are (essentially) tilt boundaries. The sense of rotation alternates between adjacent cells, across all boundaries. Dislocations in the cell walls have coplanar Burgers vectors, at right angles to the rotation axis.

Dislocation cell structures with a checkerboard pattern have often been described in the literature (c.f.2). For example, in drawn iron wire the cells are elongated parallel to the rotation axis, which is also the wire axis (3,4). Striations with a similar geometry are found in crystals drawn or grown from the melt (5,6).

In this letter we focus attention on crystals deformed in single glide, which may also contain ordered, misoriented sequences of dislocation cells (e.g., cf. Figs. 8 and 9 of (7)). We consider f.c.c. crystals, where alternating rotations about an axis close to the <112> "roller" axis (i.e. the primary edge direction) are common.

Recently, a cross-slip mechanism for the formation of dislocation structures during single glide has been developed and related to observations (8 - 12). The basic structural units produced by this mechanism are arrays of primary prismatic dislocations, stacked along $\underset{\sim}{b}$, whose internal stresses have been relaxed by secondary slip. Although at first sight these units appear to be quite different from the parallelepipedal cells predicted by the computer calculations, they are in fact the same, as we explain below. We describe the mechanism (shown in the figure) before discussing the structures it produces.

Beginning with one dipolar loop dragged out by a jogged primary dislocation (near A) a stepped trail of boxlike dislocation arrays forms (A - F). Each array consists of similar prismatic loops deposited side by side when primary dislocations in a procession cross-slip consecutively over previously formed loops. This is shown for an idealised model, which is based on observations of similar stepped trails in neutron irradiated copper single crystals (9). Each prismatic array encloses material which is strained in compression (A - D) or tension (E and F) along the primary slip direction. A detailed analysis of the stresses of the arrays (10) shows that in f.c.c. crystals plastic relaxation will occur by slip on the secondary systems A6 and C1, inside the prisms (notation of Schmid and Boas, see (13)). The three Burgers vectors (one primary, two secondary) which make up the final plastically relaxed structure are coplanar on the cross-slip plane.

The net effect of this sequence of dislocation manoeuvres is as follows. Secondary dislocations, generated inside the boxes, react with the sheets of primary edge dislocations of opposite sign which form the top and bottom of the boxes. Segments of Lomer-Cottrell dislocations form at nodes (A6 and C1 are Lomer-Cottrell forming secondary systems, with the primary system) and a distorted hexagonal network may result (cf. Figs. 2 and 3 of (14)). The top and bottom of each box are transformed by plastic relaxation to approach the configuration of tilt walls with a

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NOMENCLATURE FOR DISLOCATION ARRAYS

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Again and again, discussions among colleagues, as well as a study of the relevant publications, reveal a disturbing non-uniformity in the use of technical expressions describing dislocation arrays. This practice has led to, or perhaps is caused by, an insufficient appreciation of the actual physical differences among arrays which, as seen in TEM micrographs, may look much the same, yet have quite different properties and a different significance. It was thus considered useful to propose a nomenclature which at this point is believed to be the most widely accepted for the different types of dislocation arrays, in the hope that this nomenclature will become standard in work concerning dislocation behavior and effects of dislocations in crystalline materials.

1. Single Dislocations and Small Arrays

No definition needs to be given for edge and screw dislocations, etc. since the pertinent terms appear to be accepted and understood. Still, it may be useful to review some of the terms used for specific dislocation types and small groups even though there is little confusion regarding these.

A. Dislocation Dipoles and Multipoles

Dislocation Dipole

A relatively isolated pair of parallel dislocations with equal but anti-parallel Burgers vectors.

Vacancy-type Dislocation Dipole

A relatively isolated pair of parallel edge dislocations, or dislocations with a strong edge component, with equal and opposite Burgers vectors, not lying on the same slip plane, such that their dilated sides are nearest to each other.

Interstitial-type Dislocation Dipole

A relatively isolated pair of parallel edge dislocations, or dislocations with a strong edge component, with equal and opposite Burgers vectors, not lying on the same slip plane, such that their compressed sides are nearest to each other.

(Axial) Dislocation Multipole

A relatively isolated group of an arbitrary number of parallel edge dislocations whose axes lie as if on the surface of a cylinder or general prism, such that their Burgers vectors are normal in the same sense (e.g. all pointing inwards) to the cylinder or prism surface at their specific positions. It is a characteristic of such an arrangement that it has no long-range

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